PHASE-CHANGE FRAME WALLS (PCFWs) FOR ON-PEAK DEMAND REDUCTION AND ENERGY CONSERVATION IN RESIDENTIAL BUILDINGS: DEVELOPMENT, CONSTRUCTION, AND EVALUATION

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ABSTRACT

The main purpose of this work was to develop a thermally enhanced frame wall that would reduce peak load air conditioning demand, shift a portion of the thermal load, and conserve energy in residential buildings. A frame wall containing macro-encapsulated phase-change materials (PCMs), incorporated therein, was developed, constructed, and evaluated. This prototype wall is referred to as - phase-change frame wall (PCFW). A PCFW is a typical frame wall, consisting of outside siding, thermal insulation, studs, and inside sheathing, in which PCMs are incorporated, by macro-encapsulation, to enhance the energy storage capabilities of the wall, and thus thermal mass of the building, via the high latent heat of fusion of the PCMs. The PCFW uses off-the-shelf components, which are herein integrated in an innovative way to produce better energy performance. Results from field testing show that the PCFW offers the potential to reduce wall peak heat flux by as much as 38%. This value is dependent on climate, wall orientation, quantity of PCM, and wall insulation level. Over a period of days, the average wall peak heat flux reduction was approximately 15% when PCFWs facing four cardinal directions (i.e., N, S, E, W) were evaluated when 10% [1] concentration of PCM was used and approximately 9% when 20% PCM concentration was used. The average space-cooling load was reduced by approximately 8.6% when 10% PCM was applied and 10.8% when 20% was used. The level of fiberglass insulation in the PCFW was R-11 (1.94 m^2K/W). Although frame wall technology was used as a structural vehicle for this project, the concept could also be applied in almost any building structure, including structural insulated panels, and concrete and masonry buildings. The application could also be extended to commercial buildings.

[1] Percent PCM concentration is defined in terms of interior sheathing weight

INTRODUCTION

Commercial phase-change materials are chemicals that change from solid to liquid and back to solid as a function of desired temperatures depending on the application. During the phase-change processes, significant amounts of heat are absorbed, stored, and re-released. In building applications this could translate into lower air conditioning demand from walls and ceilings while a portion of the thermal load is shifted to other times of the day, all while the building's indoor air temperature remains relatively stable. In the wintertime, for example, heat from the furnace is stored in the PCFW, which is later released back to the heated space, thus reducing furnace cycling, which in turn increases its efficiency and equipment life.

Common phase change materials are categorized according to their melting points and latent heat values and whether they are inorganic or organic. Inorganic PCMs include several kinds of hydrated salts. Some are listed in Table 1. The attractive characteristics of hydrated salt PCMs include their price, their non-flammability, and their wide range of applications.

Table 1. Common Hydrated Salt PCMs (typical values) [Hawes et al. 1993]

PCM	Melting Point °F (°C)	Heat of Fusion Btu/lbm (J/g)
$KF \bullet 4H_2O$ Potassium fluoride tetrahydrate	65.3 (18.5)	99.3 (231)
$CaCl_2 \bullet 6H_2O$ Calcium chloride hexahydrate	85.5 (29.7)	73.5 (171)
$Na_2SO_4 \bullet 10H_2O$ Sodium sulphate decahydrate	90.3 (32.4)	109.2 (254)
$Na_2HPO_4 \bullet 12H_2O$ Sodium orthophosphate dodecatydrate	95.0 (35.0)	107.9 (251)
$Zn(NO_3)_2 \bullet 6H_2$ Zinc nitrate hexahydrate	97.5 (36.4)	63.2 (147)

Their drawbacks include their corrosive nature and the problems of supercooling. These materials are corrosive to many materials; therefore, in the case of encapsulation they need special containers. Supercooling happens when a solution cools quickly and the temperature of the solution falls below the freezing point without its solidification. Because phase-change materials work by absorbing and releasing heat as the latent heat of fusion during melting and freezing, supercooling reduces their utility. Organic PCMs include the paraffins, capric-larric acids, and palmitates. Some common organic PCMs are listed in Table 2. Among their attractive characteristics are that these PCMs are chemically stable and compatible with many holding materials and they melt congruently with no significant supercooling problems.

Table 2. Common Organic PCMs (Typical Values) [Hawes et al. 1993]

PCM	Melting Point °F (°C)	Heat of Fusion Btu/lbm (J/g)
$CH_3(CH_2)_{16}COO(CH_2)_3CH_3$ Butyl stearate	66.2 (19)	60.2 (140)
$CH_3(CH_2)_{11}OH$ 1-dodecanol	78.8 (26)	86.0 (200)
$CH_3(CH_2)_{12}OH$ 1-tetradecanol	100.4 (38)	88.1 (205)
$CH_3(CH_2)_nCH_3$ Paraffin	68-140 (20-60)	~ 86 (~200)
45% $CH_3(CH_2)_8COOH$ 55% $CH_3(CH_2)_{10}COOH$ 45/55 capric-lauric acid	69.8 (21)	61.5 (143)
$CH_3(CH_2)_{12}COOC_3H_7$ Propyl palmitate	66.2 (19)	80.0 (186)

Among their drawbacks are their cost, flammability, odor, and volume changes. The PCM used in this research was paraffin-based, which had melting/freezing points in the range of 68 – 86 ^oF (20 – 30 ^oC). Its melting and freezing profile from differential scanning calorimetric tests is shown in Figure 1.

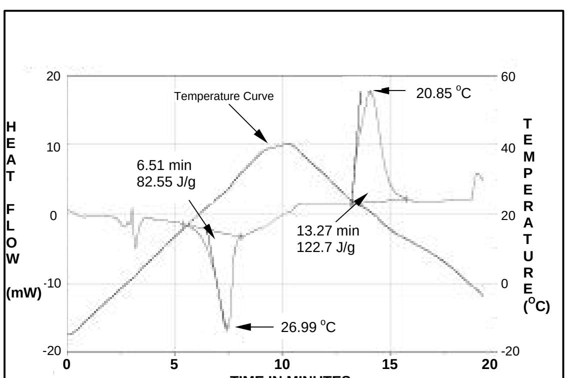


Figure 1. Differential Scanning Calorimetric Curve of the Paraffin Based PCM (Heat Flow-Time-Temperature)

As indicated in the figure, this PCM had different freezing and melting points. With about 10.8 ^oF (6 ºC) difference, its melting temperature was approximately 69.53 °F (20.85 ºC) and its freezing temperature around 80.58 °F (26.99 ºC). Both melting and freezing temperatures were within the temperature range of human comfort zone as defined and specified by *ASHRAE STANDARD 55*, "Thermal Environmental Conditions for Human Occupancy" (ASHRAE 1992). One of the potential advantages of a higher freezing temperature and lower melting one is that the PCM can be charged at higher indoor air temperature during summer and lower indoor air temperature during winter. The amounts of energy absorbed and re-released by this PCM were determined by integrating the areas under the endotherm and exotherm processes. When it melted, it absorbed approximately 52.75 Btu/lbm (122.7 J/g) of heat, and this process lasted approximately 13.5 minutes. When it froze, it released approximately 35.49 Btu/lbm (82.55 J/g) of heat, which lasted about 7 minutes.

PHASE-CHANGE FRAME WALL DEVELOPMENT

Technical developments in the field of PCMs have progressed significantly, but critical technological solutions are still needed to make this concept a practical one in buildings. Specialized techniques appropriate to particular end-uses must be developed and a better understanding of their performance under various climates is in order. Three technical feasibility issues are of critical importance for this technology if it is to become practical in building applications. One is to resolve the question of how much PCM concentration is needed for optimal performance in a variety of climates. This issue is interrelated with the other two, which are the heat transfer rate across the wall of the encapsulating pipes and the rate of recharging (the cyclical heat release/phase change) of the PCM inside the pipes. Preliminary analyses related to these issues have been conducted, which provided guidance and some answers. These are still being verified via experimental and analytical work. From these analyses, it was determined that the optimal amount of PCM concentration is between 10 and 30%; more specifically, between 15 and 25% depending on weather. Further iterations are needed using real weather data in various climates. Also, it was established that pipe material (i.e. copper, aluminum, or PVC) was not as critical as originally thought. Modeling results showed that wall insulation was the determining factor in the heat transfer rate to and from the PCM, and not the pipe material. In addition, it was resolved that by placing the pipes in contact with the interior face of the interior sheathing, the rate of recharging the PCM was superior than when the pipes were placed in the middle of the insulation or in contact with the outer sheathing layer. The pipes were placed horizontally and were attached to the studs using brackets. The insulation level used was R-11 (1.94 m^2K/W). The preliminary modeling indicated that indoor convection, insulation thickness, indoor air temperature, and outdoor air temperatures affected the rate of recharging. Further studies are needed. Based on these findings a Phase-Change Frame Wall (PCFW) was developed. A schematic of the prototype is shown in Figure 2.

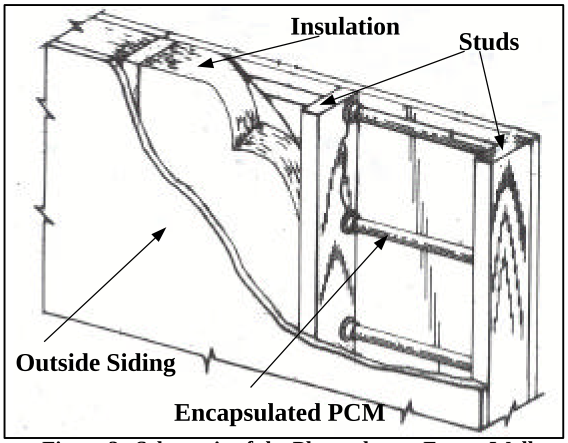


Figure 2. Schematic of the Phase-change Frame Wall

The concept of the phase-change frame walls is innovative in at least two respects: the PCM containment method and the use of the concept in upcoming technologies, such as panelized frame walls. In the past, the attempts to improve the energy efficiency of walls and ceilings by the application of thermal mass using the heat storage available during the phase-change process were met with mixed results (Salyer and Sircar, 1989). Various PCMs were utilized for this purpose, which were mostly introduced by imbibing them into gypsum boards. This system demonstrated many advantages in energy savings; however, two main problems limited their potential application: durability of PCM-impregnated gypsum boards and low fire rating (Banu et al; 1998). In the proposed walls, a macrocapsule containment method (MCM) rather than an imbibing method (IM) was used. The MCM is safer and more stable than the IM because PCMs are first encapsulated in pipes, which are then capped at both ends to prevent leakage. The capsules are assembled within the wall and held in place by brackets attached to the sides of the studs (refer to Figure 2). Thus, no holes are drilled across the studs, which otherwise could reduce their structural properties. In the IM, the PCM is infused into the gypsum board. The MCM should be the preferred method because it eliminates PCM dripping when PCMs melt, reduces the flammability of the wall, and eliminates the moisture transfer problem across the envelope. The IM decreases the permeability of the wall, thus creating indoor humidity problems. In addition, because the pipes are never completely filled with PCM, problems associated with PCM volume changes during the phase change process are eliminated. The MCM also eliminates problems associated with contact between PCM and wall coatings/finishes and between PCM and people.

As mentioned above, this concept could be accepted by the frame wall *panel* industry, which is also innovative. Panelizing is the process of taking lumber, precutting it, and producing a wall panel in a factory under controlled conditions. The advantages of panelizing are several. First, the use of panels permits the closing-in of a house in a week's time (or less) depending on the size of the house. This promotes faster, easier, and lower cost methods of erecting structures. For example, a 1,750-ft^2 (162.6 m^2) house can be erected in less than three days. This avoids delay costs and avoids waste and loss due to weather and pilferage of materials lying around. Panelizing also gives design flexibility because panels can be manufactured in sizes from 4 ft to 18 ft (1.22 m to 5.49 m), thus saving on engineering and design costs. The use of wall panels could make the walls stronger and the buildings more airtight, thus making them more comfortable, more energy efficient, and quieter. By combining the panelizing with PCM, manufacturers could control the levels and kinds of PCM used in the panels. This is important because it is believed that different PCM levels or kinds of PCM would be required depending on climate.

FIELD TESTING

<u>*Experimental Setup*</u>

A set-up consisting of two 6 ft x 6 ft x 4 ft (1.83 m x 1.83 m x 1.22 m) identical test houses of conventional residential construction with scaled down heating and cooling systems was used. Both test houses were instrumented to monitor and record space cooling and space heating energy consumption, indoor air and surface temperatures, indoor air relative humidities, outdoor surface temperatures, and wall heat transfer. One house was used as a control house and the other as a retrofit house. A weather station that measured outdoor air temperature and humidity, wind speed and direction, and total solar radiation was used to collect relevant weather data. A picture of the test houses is shown in Figure 3. To condition the indoor air of the test houses, a chilled water system was assembled where water was chilled down to 40 ^oF (4.4 ^oC) with a small immersion refrigerator. Pumps circulated the chilled water through fan-coil-units (FCUs) placed inside the houses. The inside air temperatures of both houses were maintained to a maximum average difference of less than 0.5 ^{o}F (0.27 ^{o}C) . No shadow from trees, buildings, or other obstructions was allowed.

Figure 3. Test Houses

Instrumentation

Type T thermocouples (T/C) were used to measure temperatures. Heat flux meters (HFMs) measured heat fluxes across the walls. Relative humidity transducers measured indoor and outdoor air humidity levels. In addition to the instrumentation in the houses, ambient air temperatures, ground temperatures, wind speed and direction, and global sun and sky radiation were measured at the site. All surface and air temperatures were measured using T/C grid groupings connected in parallel and the T/Cs were shielded to minimize radiation effects. For instance, a grid of nine T/Cs measured the temperature of each surface of the walls (see Figure 4). These nine temperatures were then averaged to provide a single wall temperature.

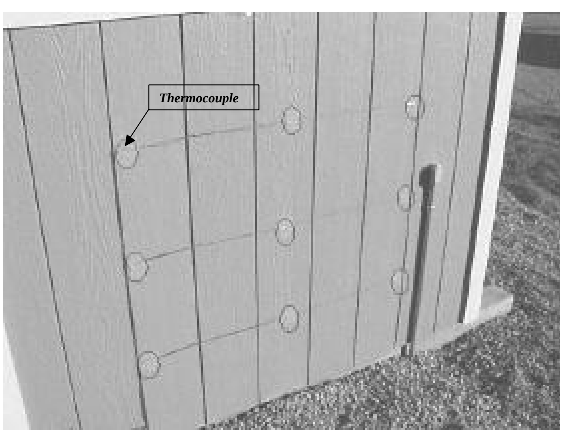
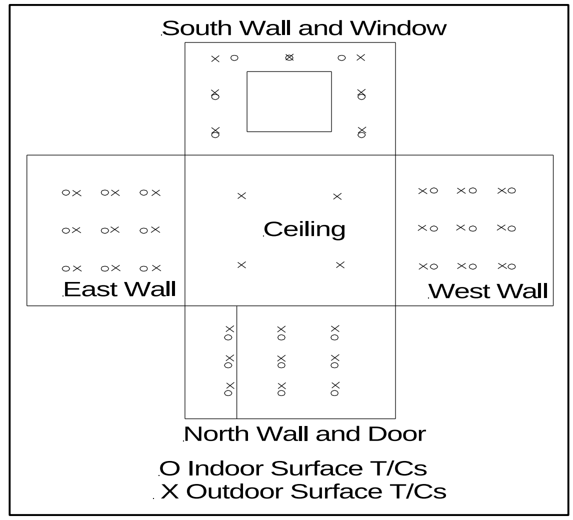


Figure 4. T/C Grid Locations (East-facing Wall)

Figure 5 shows a schematic of the location of all surface temperatures.

Figure 5. Location of All Surface Temperatures



Each wall was fitted with two heat flux meters with dimensions of 4 in x 4 in x 3/32 in (10.2 cm x 10.2 cm x 2.4 mm). The HFMs were attached with high conductivity adhesive. Their locations were selected to represent positions directly over pipes and midway between two pipes. The flowrates of the chilled water into each house were be monitored with precision flow control rotameters. The water flow rates were used to estimate space-cooling loads.

Climate

The city of Lawrence, Kansas, enjoys the distinctiveness of not only the four seasons with hot and humid summers and cold winters, but of swing seasons with a wide range of ambient air temperatures, insolation, wind speeds, and humidities. Over the past 30 years temperatures varying from -26 ^{o}F to 110 ^{o}F (-32.2 ^{o}C to 43.3 ^{o}C) have been recorded. The mean relative humidity estimated at noon Central Standard Time ranges from 88 percent in August to 78 percent in January. The percent of possible sunshine is estimated at 69 percent during summer and 61 percent during autumn (National Climatic Data Center, 1999). Weather variations such as those experienced in Lawrence make it ideal to conduct this type of study. Under this region's weather, which offers both relative extremes and almost everything in between, studies can produce results that can be adapted to many areas of the country.

RESULTS AND DISCUSSION

Calibration

It was necessary to perform calibration tests before every retrofit. The thermal performance of the two houses was compared and recorded as reference. Heat fluxes and average wall temperatures as well as indoor air temperatures were measured and compared to verify the similarity of thermal capacity for both houses. Samples of how the temperatures compared are shown in Figures 6 and 7 and how the wall heat fluxes compared is shown in Figure 8.

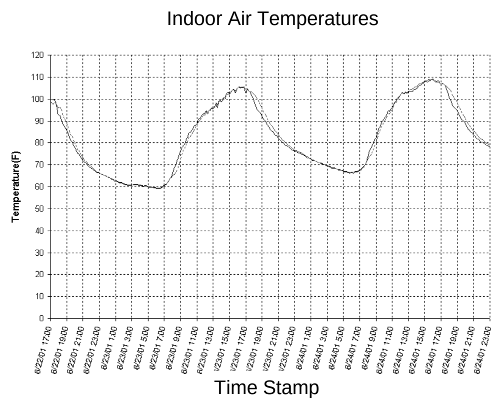


Figure 6. Indoor Air Temperature Comparisons (Uncontrolled)

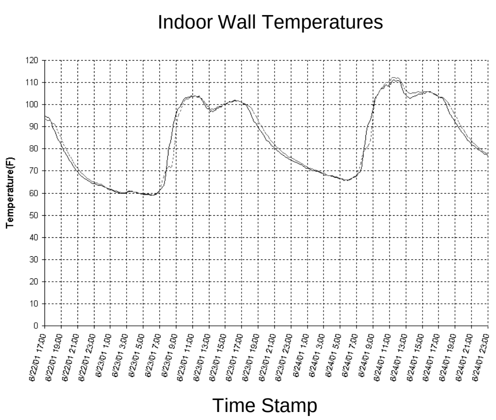


Figure 7. Indoor Wall Temperature Comparison (Uncontrolled)

In Figures 6 and 7 the darker solid line represents the temperature of the control house. Figure 6 depicts how the indoor air temperature varied over a period of time when the test houses were not climate controlled. Figure 7 depicts the same concept but for the walls of the test houses. The point of these figures is to show how close the indoor temperatures were after construction meaning that both houses were nearly identical in their thermal responses, mainly in their ability to absorb and store heat. The average difference in temperatures in the figures above was less than 0.5 ^{o}F (0.27 ^{o}C). In Figure 8, west-facing wall heat fluxes are depicted prior to any

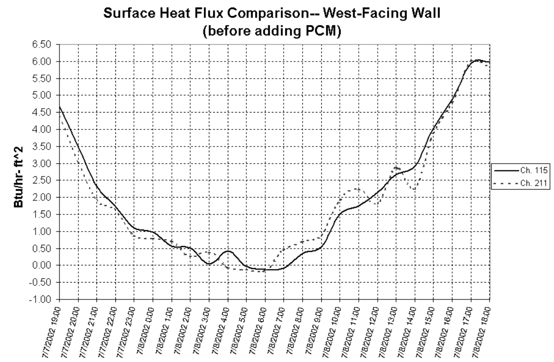


Figure 8. Surface Heat Flux Comparisons (West-facing Wall – Controlled Conditions) (Solid Line: Control House – Dashed Line: Retrofit House)

retrofit. The information on this figure differs from the information of the previous two graphs in that in Figure 8 the indoor space was climate controlled. The average difference in heat fluxes was estimated at less than three percent. The peak heat fluxes were identical, however.

Summer Results

Data presented in this section include comparison graphs of heat fluxes when 10% (Fig. 9) and 20% (Fig. 10) concentrations of PCM were applied. In addition, a set of graphs (Figs. 11 and 12) corresponding to the times of Figs. 9 and 10 are presented to show the degree of control in indoor air temperature when the tests were conducted. Because of space only a few data are presented. More specifically, the data are from west-facing walls. For more data and experimental details and analyses refer to Zhang (2004). These walls were in fact the ones that received most of the daily solar radiation.

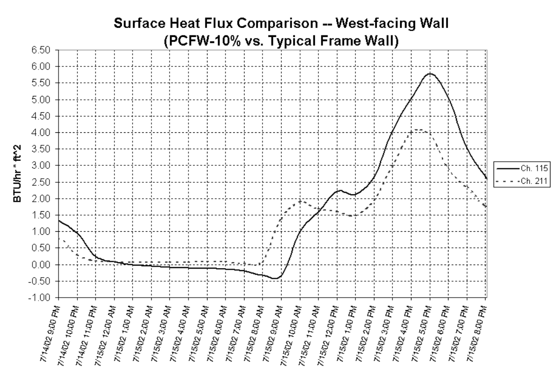


Figure 9. Surface Heat Flux Comparisons (West-facing Wall – Controlled Conditions) Solid Line: Control House with Typical Frame Wall Dashed Line: Retrofit House with Phase-change Frame Wall at 10% Concentration

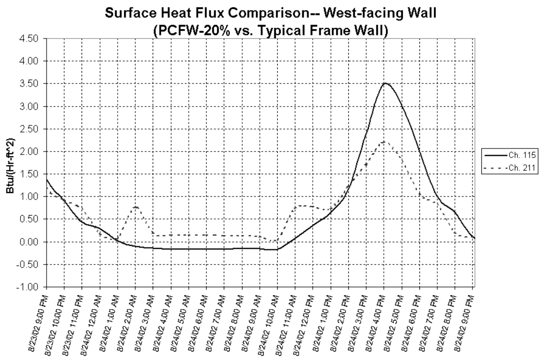


Figure 10. Surface Heat Flux Comparisons (West-facing Wall – Controlled Conditions) Solid Line: Control House with Typical Frame Wall Dashed Line: Retrofit House with Phase-change Frame Wall at 20% Concentration

Data for all other walls, except the east-facing wall are available. Data for the east-facing wall was disregarded because the fan coil units were attached to this wall, and because of the size of the test houses, little space remained for the installation of the sensors.

From the data plotted in the previous figures it is clear of the impact that the integration of phase-change materials has on the thermal performance of walls. While the peak heat fluxes in Figure 8 (calibration) were nearly identical, the difference in peak heat fluxes when the concentration of PCM was 10% resulted in approximately 31% (Figure 9) and in approximately 38% when the concentration of PCM was 20% (Figure 10). Figure 11 depicts hourly indoor air temperatures for both houses related to the date and times of Figure 9. Figure 12 depicts hourly indoor air temperatures for both houses related to the date and times of Figure 10.

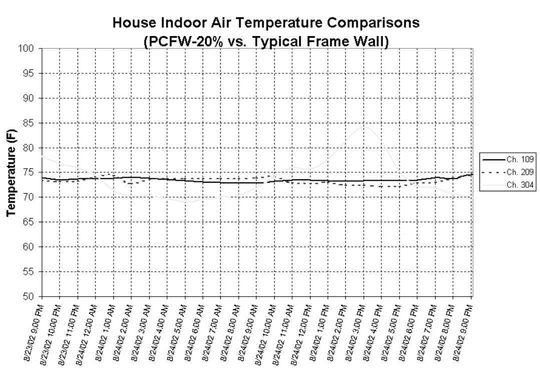


Figure 11. Indoor Air Temperature Comparisons (Controlled Conditions) Solid Line: Control House with Typical Frame Wall Dashed Line: Retrofit House with Phase-change Frame Wall at 10% Concentration

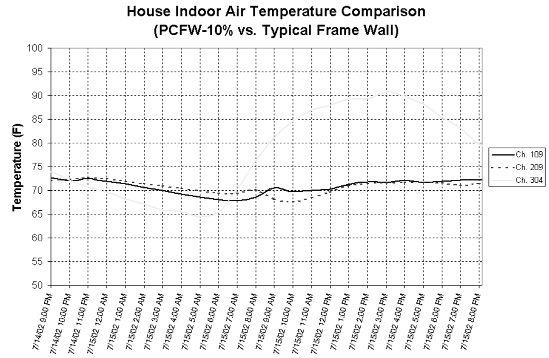


Figure 12. Indoor Air Temperature Comparisons (Controlled Conditions) Solid Line: Control House with Typical Frame Wall Dashed Line: Retrofit House with Phase-change Frame Wall at 20% Concentration

From the data plotted in Figures 11 and 12, it was determined that the average indoor air temperature differed by no more than 0.5 ^{o}F (0.27 ^{o}C). This fact should give more validity to the impact of the phase change materials.

As expected, the peak heat flux through any wall depended on the orientation of that wall. For both test houses, the west wall had a heat flux that was approximately twice that of the north wall. When all data for various days under different summer weather variations were compiled it was determined that the peak heat fluxes were reduced by 11%, 21% and 13% for south, west and north wall, respectively when the concentration of PCM was 10%. For 20% PCM, the peak heat fluxes decreased by 1%, 12% and 15% for south, west and north wall, respectively. This information is for one summer only. More experiments are needed to verify these results.

It was observed that whenever the average outdoor air temperature was higher than both houses' average indoor air temperatures, the control house had a slightly higher average indoor temperature. When the outdoor temperature was lower than indoors, the retrofit house had higher average temperatures. Although lower during period of solar activity, the heat fluxes through the walls in the retrofit house were mostly into the conditioned space (positive), even during periods of no solar activity and/or when outside temperatures were relatively low. During daytime hours when the outdoor temperature was higher than indoors, the PCM absorbed a part of heat transferred from the exterior wall surface and stored it in state of its latent heat. During the night when outside temperatures dropped, the PCM released the heat stored during the day. This heat was transferred into the interior sheathing wallboard and in the opposite direction through the insulation and exterior siding. Because the resistance to the transfer of heat was lower towards the interior side, more heat would flow into the inside space. This phenomenon indicated that PCM helped the house maintain the indoor air and surface temperatures at more constant values offsetting the effect by the outdoor air temperature swing in the indoor temperatures, which can increase the comfort level. An example of this is shown in Figure 13. In addition, the operating life of the cooling equipment may also be prolonged because less "ON/OFF" operation was required. Because some of the stored heat was transferred to the indoor while some went to the outdoor, a net lower total heat transferred was noticed in the retrofit house. This is depicted in Figure 14.

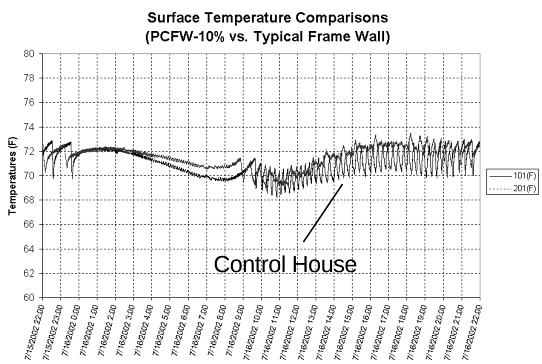


Figure 13. Wall Surface Temperature Comparisons (Controlled Conditions)

Figure 13 depicts how the PCFW is able to keep a more constant temperature and a narrower temperature swing than the standard wall, which in turn should increase occupant comfort.

In terms of overall cooling load, it was made clear that the retrofit house consumed less energy for cooling as the testing progressed from the calibration to retrofitting with PCFW at 10% concentration to retrofitting with PCFW at 20% concentrations.

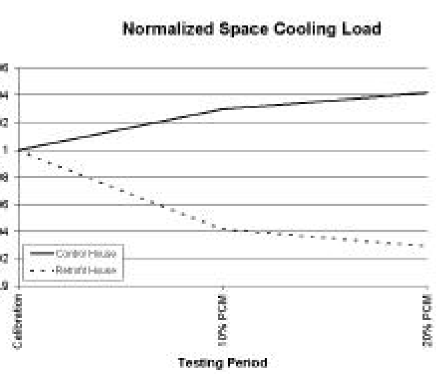


Figure 14. Normalized Space Cooling Loads
Solid Line: Control House with Typical Frame Wall
Dashed Line: Retrofit House with Phase-change Frame Wall at 10% and 20% Concentrations

As the tests progressed, the ambient conditions became warmer, thus the increase in space cooling load indicated by the solid line, which represents the control house. In the retrofit house, however, the space-cooling load decreased even when the ambient conditions were hotter. A simple statistical analysis of pre- and post- retrofit data suggested that by using PCFWs at 10% concentration the test house would reduce its cooling-load requirement by 8.6%. At a PCM concentration of 20% the cooling load would be reduced 10.8%.

As one of the key parameters to affect the comfort level, relative humidity (RH) was also monitored before and after the application of PCM. The major concern emphasized on whether the addition of PCM would increase the indoor air RH dramatically. The results indicated that indoor air relative humidity was not affected by the retrofit. This is shown in Table 3.

Table 3. Average Indoor Air Relative Humidity Comparison

	Control House	Retrofit House	Diff. (CH – RH)
No PCM	68.08 %	72.55 %	4.47 %
10% PCM	64.77 %	69.07 %	4.30 %
20% PCM	65.09 %	69.90 %	4.81 %

The sensor in the retrofit house recorded higher average values since the calibration of the test houses, which was about 4.5% higher. There were no significant RH value increases after applying 10% and 20% PCM. The RH difference between the houses remained as 4.30% and 4.81% for 10% and 20% PCM addition, respectively.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

The purpose of this research was to develop, construct, and evaluate a phase-change frame wall (PCFW) prototype. The prototype was developed and then constructed based on analyses that integrated the performance of its individual components. Afterwards, two wood-framed test houses were constructed and then equipped with space heating and cooling systems. A monitoring system was installed to measure and collect space-cooling load and thermal performance parameters including temperature, heat fluxes, relative humidities and weather parameters. A paraffin-based phase-change material with a melting/freezing range of 68 to 86 °F (20 – 30 °C) was selected as the PCM for this research. Differential scanning calorimeter (DSC) tests were performed to determine the exact melting and freezing points and specific heat. The

PCM was encapsulated in copper pipes, which were later placed just behind the interior sheathing layer. Ten and 20% percent PCM concentrations of the PCM were tested and evaluated during the summer season.

The peak heat fluxes through the PCFWs were substantially lower than for the standard wall. When all orientations were considered, the average peak values decreased from 11% to 21% for a 10% PCM concentration and from 1% to 15% for a 20% PCM concentration. The west and north walls achieved more heat rate reduction compared to the south wall. As for load shifting, it was observed that the “shift” was spread over many hours from about midnight until about 1 PM. The cooling load was reduced from 8.6% to 10.8% for the 10% and 20% concentrations, respectively. The relative humidity of indoor air did not increase for the retrofit house.

Recommendations

The performance of PCFWs depends on weather conditions, such as average solar radiation gain, diurnal temperature swing range, wind speed, among others. Usually, regions with larger diurnal temperature swing ranges should take more advantage of this concept for cooling load reduction. The application of phase change building materials should be highly recommended for the regions where there are relatively wide diurnal temperature swings. The optimal scenario is for hot days and cool nights. Under this scenario, annual cooling load could be significantly reduced. Whether the benefit of the application of PCFWs can be acquired would be based on several factors that must be considered. For example, the phase-change material and the location of the encapsulated PCM within the wall have to be carefully selected considering PCM thermal behavior and performance. Also, special air conditioning and ventilation modes are required to optimize the performance of PCFWs. For regions with relatively low temperature, lower than set point temperature, during night, more ventilation with outside air should be introduced to flush the stored heat flow. An outdoor air temperature sensor could be included in the Air Handling Unit (AHU)’s control system, so that a fan would operate when the outside temperature is below the thermostat set-point temperature. With this function, the PCM components within the wall construction could be cooled and recharged during “off hours”. If possible, passive solar design should be applied to enhance the effect of PCM application for winter. In addition, mathematical models need to be prepared and run to simulate the heat transfer process.

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